MILKLINE CLEANING DYNAMICS:
DESIGN GUIDELINES AND TROUBLESHOOTING

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Introduction

Most modern milking systems are cleaned using air injected CIP systems. Cleaning and disinfection is accomplished by a combination of physical, thermal and chemical processes. The circulation of sufficient volume of cleaning solutions at sufficient velocity and temperature is required to adequately clean milk contact surfaces. Failure of CIP systems often results from inadequate velocity or contact time of the cleaning solution. A small amount of residual soil can facilitate bacterial attachment, survival and growth. If not inactivated or removed during cleaning, remaining bacteria may eventually detach and contaminate the milk supply. This may affect the quality and, if pathogens are present, the safety of the milk.

Current methods for clean-ability assessment of CIP treated milking systems employ microbiological tests (standard plate count). There are several limitations to the use of these tests. First, they require several days to obtain results, and second, it is difficult to locate the source of the cleaning failure. Cleaning problems are generally detected by elevated bacterial counts in the product after many soiling/cleaning cycles. When this occurs, bacterial contamination is likely to have had effect on a large volume of product. The development of rapid and reliable methods to assess cleaning will improve the design, installation and performance of cleaning systems and thereby improve milk product quality and safety. This paper presents the results of a theoretical and experimental study performed to characterize the dynamics of air injected CIP flows and presents preliminary recommendations for the design and trouble shooting of milking CIP systems.

Air Injected CIP Flow Dynamics

The amount of hot water and detergents required to flood pipelines increases proportionally with the square of the pipeline diameter. Air injection has been widely used on milking CIP systems to produce 'slug' flow in milklines. Air injection increases the circulating velocity of the wash solution and reduces the water requirements for cleaning when compared to fully flooded lines.

Slug flow is characterized by the passage of discrete liquid slugs. The slugs usually have a significant volume of gas bubbles entrained in them. Slug length may vary from a few centimeters to several meters. The area between the slugs contains a slower moving liquid layer in the bottom of the pipe with air moving at approximately the slug velocity above the liquid layer.

The objective in air injected flow is to form a 'slug' of cleaning solution and move this slug around the system to provide adequate turbulence and contact time on all surfaces to perform the cleaning and sanitizing functions. The formation of a single slug in milking CIP systems occurs because of the cyclic introduction of air and water.

Experimental Apparatus

The experimental system consisted of two straight 36 meter pipe sections with 73 mm inner diameter (3 inch nominal diameter) joined by a 180° U bend. Shorter runs of 48 mm and 98 mm (2" and 4" nominal) pipelines were also tested. Each pipe section was sloped to drain toward the receiver jar with an inclination of 1 %. A wash valve was installed in the pipeline between the point of water entry and the receiver jar. This valve is closed during the cleaning process to prevent short circuiting of cleaning solution to the receiver jar. The cleaning solution is directed through the entire pipe loop, traveling first uphill in the first pipe section leg and downhill in the return leg. A transparent acrylic section was installed at both the beginning and end of the pipe loop for flow observation.

The cleaning solution was transported from the wash tank into the system through a 35 mm (1.5") stainless steel pipe. A pneumatically actuated air injector was mounted at junction of the wash supply line and the milk pipeline. When the air injector is in the 'closed' position, cleaning solution is drawn by vacuum from a wash tank into the test loop. The air injector is then switched to the "open" position allowing air at atmospheric pressure to enter the pipeline. This stops the draw of cleaning solution from the wash tank and propels the cleaning solution around the pipe circuit. The amount of the cleaning solution drawn into the system during one air injection cycle can be controlled by the air injector "close" time.

The air flowrate entering the system through the air injector during the injector 'open' phase was controlled by using orifice plates offering varying restriction to air flow. The system vacuum was generated by a liquid-ring pump with a maximum air flow capacity at 50 kPa (15" Hg) vacuum of 3000 L/m (110 scfm). The pump displacement could be reduced to half of its full capacity by isolating one half of the pump from the system. Further details of the experimental apparatus, procedures and results are presented in Reinemann et al, 1992 (1).

Experimental Results

Conditions for slug formation and maintenance: The air injector open and closed time settings required for the production and maintenance of a slug around the 72 meter (236 ft), 73 mm (3 in) diameter test loop are shown in Figure 1. Note that the injector cycle times required to consistently form and maintain a slug are longer than those commonly encountered in round-the-barn pipeline systems of equivalent pipeline length in the field.

The slug acts, in some respects, like a wave as it moves through the pipeline. It picks up liquid at its face and loses liquid at its tail as it travels. As will be shown, the rate of water pickup is directly proportional to the fill depth in the pipe ahead of the slug. If the standing liquid layer in the pipe is not of sufficient depth the slug length will lose liquid at its tail faster than it is being accumulated at its face. The slug will therefore, decrease in length until finally it disappears. This process occurs during the first several air injection cycles as the liquid layer is forming. After several cycles an equilibrium is established between the water being admitted and removed during each injection cycle. If too little water is drawn in during each cycle (injector close time too short) the liquid layer in the pipe bottom will be depleted. Likewise, increasing the duration of air flow (by increasing the injector open time) acts to reduce the amount of water remaining in the pipeline. If the bottom film is not of sufficient depth the slug breaks before completion of the pipeline circuit.

Increasing the amount of water drawn in during each cycle (increasing injector close time) and decreased duration of air flow (decreasing injector open times) act to increase the film depth in the pipeline. This results in very large slugs which flood the receiver. If the injector open time is not sufficient to allow the slug to completely travel the pipeline circuit, the slugs break and travel the remaining distance to the receiver as a wave. The combination of short open <u>and</u> close phases results in a high film depth (50 - 60% of the pipe), and low velocity slugs reaching the receiver occasionally (i.e. not on each injection cycle). It is difficult to assure that all surfaces are receiving adequate turbulence and contact time when this condition exists. The water flow to the receiver is this situation also tends to be extremely variable and it is difficult to prevent flooding.

There are four requirements for consistent slug formation and maintenance, based on these observations:

Sufficient liquid volume to form a slug at the beginning of the pipe circuit.

Sufficient standing liquid layer in the pipe to maintain the slug during its travel

Sufficient volumetric air admission rate to form and maintain the slug.

Sufficient duration of air flow for the slug to completely travel the pipeline.

<u>Air flowrate and vacuum relationships</u>: Typical pressure traces with a highly restricted air injector opening (13 mm, 0.5 " orifice) an unrestricted air injector (38 mm, 1.5", orifice) are shown in Figures 2 and 3. If the pump capacity is larger than the air flow being admitted the system vacuum will be maintained (Figure 2). If the air admission during the injector open phase exceeds the air removal capacity of the

pump, the overall system vacuum and vacuum ahead of the slug will fall (Figure 3) . The rate and magnitude of the vacuum drop will depend on the air flowrates entering and being removed and the total volume of the system. Considerable energy can be stored in the system and released during air admission by when the system vacuum fluctuates. Increasing system vacuum level and increasing system volume both act to increase the amount of stored energy available. This stored energy can compensate for an undersized vacuum pump if the injector close phase is long enough to allow the vacuum pump to recover system vacuum.

The pressure at the tail of the slug is atmospheric pressure minus frictional losses at the entrance (through the air injector) and losses as the air travels through the partially filled pipe. As the air injector opening is reduced the air flow rate entering the system is reduced. The pressure at the beginning of the pipe is also reduced (vacuum level is increased) which reduces the pressure difference driving the slug. The reduced pressure (increased vacuum) in the system may also prevent the feed line from draining or result in water being drawn in to the milkline during the injector open phase.

The system can thus be controlled by adjusting injector open and close times, restriction to airflow through the air injector, system vacuum set point, and restriction to water entry in the wash draw line. The system volume and vacuum pump capacity may also be adjusted during installation.

<u>Bottom film velocity and fill depth</u>: The percentage of pipe cross section occupied by the bottom film at the end of the injector close phase is shown in Figure 4. During the injector closed phase the film is draining from the high point to the receiver jar. This causes a thinning of the bottom layer near the high point and a buildup of the layer near the wash valve. Cleaning solution is also being added to the pipe at this point, accounting for a major increase in the depth of the bottom layer. The bottom layer at the end of the pipeline, at which point it is free to drain into the receiver, remains relatively constant.

The two forces propelling the bottom layer are gravity and the shear created by the faster moving air over the film. Gravity acts to move the film in the opposite direction to the slug in the first half of the pipe and in the same direction as the slug in the second half of the pipeline. The measured velocity of the bottom layer between slugs ranged from 0.4 to 0.8 m/s. When the slug passes, the bottom film is rapidly accelerated to the slug speed. This is an indication that the slug is a region of intense liquid mixing. There is a long 'tail' in which the liquid being shed from the slug decelerates and stratified flow redevelops.

<u>Local slug length</u>: The local slug length measurements are presented in Figure 5. The cleaning solution is introduced into the milk line at the bottom of one slope. A slug is formed immediately upon opening of the air injector. The slug length increases rapidly in the initial pipe section. The slug length grows to a length substantially longer than can be accounted for by the water injected. This is because the slug is

picking up water from the bottom layer in the pipe.

The growth rate of the slug is directly related to the fill depth. This adds to the initial water charge and accounts for the rapid growth of the slug in the early portion of its traverse. After about 20 meters of travel the slug length begins to decline for the rest of its travel through the loop. This is an indication that the rate of water shed at the tail of the slug is higher than the rate of water pick up at the leading face of the slug.

Local slug velocity: The local slug velocities for the various air injector restrictions are illustrated in Figure 6. The slug is rapidly accelerated and reaches a relative maximum in the first few meters of pipe. The velocity then stabilizes, or slowly increases depending on system parameters. As the slug shrinks the resisting frictional forces are reduced. The slug driving pressure also decreases as the slug travels along the pipe. If the resisting frictional forces decrease faster than the driving forces, the slug accelerates. In the cases with high air flowrates the slug accelerates rapidly near the end of the pipeline and dissipates.

Air to water velocity ratio, estimates of slug void fraction: A parameter of interest in two phase flow is the slip coefficient. This coefficient is a measure of the relative velocities between the air and liquid. The slip coefficient also gives an indication of the void fraction of the slug.

The slip coefficients were regressed against the pressure difference across the slug, slug velocity and slug length. Both pressure difference and slug length produced significant correlations. Increased pressure difference across the slug and a shorter slug resulted in a higher the slip coefficient. The greatest effect was due to the pressure difference across the slug. The ratio of the actual air and slug velocities ranged from about 1 to over 2. The inverse of this velocity ratio is an estimate of the slug void ratio (water volume/total volume). The slug void fraction based on this method of estimation ranged from 0.5 to 1 with most values falling between 0.7 and 0.8. These values correspond with estimates made from high speed photographs of the slugs.

The slug acts as an imperfect piston resisting the pressure differences across it which act to propel it through the pipe. As the pressure difference across the slug increases, the 'slip' between the air and water increases. Thus increasing the pressure difference across the slug does not produce a proportional increase in slug velocity.

Average local wall shear stress: The wall shear stress can be calculated from the slug velocity, and slug density. The pressure difference across the slug can also be used to estimate the shear stress on the pipe wall if corrections are made for the other factors affecting the force balance on the slug. The pipe wall shear stresses are illustrated in Figure 7. These are average shear stress around the pipe cross section (i.e. top to bottom). Further investigations were done to determine the distribution of shear stresses around the pipe section.

The shear stresses developed in air injected flows are considerably higher than those found in fully flooded flows. Note from Figure 7 that the shear stresses are relatively uniform along the pipe length for the two smaller injector orifices (lower air flow rates). With the largest injector orifice (highest air flowrate) there is little increase in the average shear stress along the pipe length but considerably more variation (i.e. some parts of the pipe are subjected to substantially higher shear stress than others).

This indicates that it is possible to inject too much air into the pipe. Excessive air admission will increase the slip coefficient (ratio of air to slug velocity) and also increases the amount of air entrained in the slug. Increased air in the slug reduces the shear stress it is capable of developing and also acts to break down the slug. This phenomena was observed for 73 mm and 98 mm (3" and 4") pipelines. In 48 mm pipelines, increasing the air injector opening from 13 mm to 38 mm (0.5" to 1.5") did not result in substantially higher air flowrates. This is because the maximum airflow rate is limited by the friction in the pipe itself rather than by the restriction at the air injector.

Assessment of mechanical cleaning action: A method described by Grasshoff, 1983 (2) was used to assess the mechanical cleaning action of air injected cleaning flows. Anhydrous butterfat was melted, dyed with sudan red and applied to the interior surface of an acrylic pipe section. The coating process resulted in a layer of crystallized butterfat of about 1 mm thick on the interior of the acrylic section. The test section was then placed in the cleaning circuit and subjected to specified flow conditions using a solution of 0.3% NaOH maintained at a temperature above the melting point of the butterfat. The residual butterfat was then removed from top and bottom halves of the test section independently using petrol ether as a solvent. The concentration of the residual butter fat dissolved in the petrol ether was then measured using a spectrophotometer. The results of one series of butterfat tests is shown in Figure 8.

The acrylic surface is hydrophobic (repels water) while melted butterfat adheres to it. A balance is established between the mechanical forces acting to remove the melted butterfat (pipe wall shear stress) and the attractive force adhering the butterfat to the acrylic surface. The level of residual butterfat is thus an indicator of the mechanical cleaning action which has taken place. A very good correlation was found between the butterfat residue and the wall shear stress determined by detailed flow measurements.

Bacteriological studies are being used as another method of assessing mechanical cleaning action. A section of stainless steel pipe has been constructed with removable, stainless steel test chips mounted flush with the interior of the pipe wall. The stainless steel section is inoculated with bacteria, placed in the milking system and subjected to specified flow conditions. The test chips are then removed and examined under a scanning electron microscope. A florescent dye technique is used to distinguish between living and dead cells and standard plate culture is performed.

These tests indicate the combined effects of mechanical shear stress and contact time on removal of bacteria from the pipe surface. These tests are currently underway. Future work will be directed at investigating the interactions between mechanical, thermal and chemical cleaning actions. Final confirmation of the level of shear stress required for adequate cleaning action will be obtained after completion of the bacterial and chemical studies.

Applications for milking CIP systems: Some preliminary recommendations can be made based on the results of these flow studies.

Air injector timing: It is necessary to form one slug and maintain that slug around the entire pipe loop to assure that all pipe sections have adequate contact and turbulence. Average slug velocities range from 6 to 10 m/s. Thus to determine the approximate length of the injector open phase in seconds divide the total pipe length in meters by 8 (divide pipe length in feet by 25). For a typical round-the-barn pipeline of 90 meters (300 ft) the injector open time should be about 11 to 12 seconds. The injector close time should then be increased until a slug reaches the receiver with enough volume to thoroughly wash all of its surfaces. Fine adjustments can then be made to the injector open time so that the injector closes just before the slug reaches the receiver. A method of adjusting the effective air injector restriction and thereby air flowrate entering the system allows for considerably improved control over the air injection process.

Pipeline configuration: It is very difficult to assure that all sections of milklines with multiple flow paths ('Tee' or 'Y' lines) will receive adequate slug action, particularly if the two sections are of unequal length. The air injector timing can be optimized for only one side of the line. The other side is likely to be over or under filled. One solution to this problem is to separate the pipeline into two separate flow circuits and supply each circuit with its own air injector. Another possible solution is to install an automatically controlled wash valve at the intersection and use a 4 cycle air injector (i.e. separate open and close phases for each loop).

Estimating water requirements for cleaning: The average fill fraction of the pipeline ranged from 15 to 25 percent when good slug formation was achieved. A range of 20 to 25 percent of the pipe volume should be used for estimating the water required for each cleaning cycle if the system is set up as describe above. This water is in addition to the reserve water volume required for the receiver, wash vat, milking units and ancillary equipment.

Vacuum levels: The vacuum difference across the slug decreased as line diameter increased. This is because the slug must support the pressure difference across it. As the line diameter increases the wall of water that is the slug looses its ability to seal the pipe cross section. In large diameter lines, [73 mm (3") or greater] the vacuum level in the system may be dropped without loss of cleaning performance. The vacuum pump will run more efficiently and the 'slip' of air past the slug will be reduced. The restriction through the air injector must, however, be decreased to allow enough air to enter the system.

Required air flows: The range of airflows required to form and maintain a slug and the average slug velocity produced for a single loop of different diameter pipelines are given below:

Line diameter	Air flow rate	Average slug velocity
48 mm (2")	450 - 750 L/m (16 - 26 scfm)	7 - 10 m/s (23 - 32 ft/s)
73 mm (3")	850 - 1500 L/m (30 - 55 scfm)	7 - 10 m/s (23 - 32 ft/s)
98 mm (4")	1700 - 2500 L/m (60 - 90 scfm)	7 - 10 m/s (23 - 32 ft/s)

Note that the increase in slug velocity and resulting shear stress is not directly proportional to the superficial air velocity. This is because the slip coefficient increases as more air is admitted into the system. A larger pipe diameter will also increase the slip coefficient. Increasing airflow above the maximums suggested above will not improve cleaning action in the milkline. A vacuum pump smaller than the suggested levels will provide adequate cleaning action if the system volume is large enough to provided sufficient stored energy.

These air flows will generally be met or exceeded by recommended air flowrates for milking. These should be considered preliminary results as investigations into the interaction of mechanical and chemical cleaning processes have not been completed. These air flowrates also apply only to single looped pipelines. Milklines with Tee's or Y's (introducing a second flow path) and parlor CIP systems may require higher air flowrates. Investigations into these systems are continuing.

Setup and Troubleshooting of Milking CIP systems : A slug produces a very definite vacuum drop signal in the milkline (Figures 2 and 3). A pulsation analyzer with sufficiently rapid response time is an excellent tool for the setup and trouble shooting of milking pipeline CIP circuits. Pressure traces done at various points along the milkline will provide information as to the presence of a slug in the line. If air injection settings are correct and a good slug is formed and maintained, the vacuum drop as the slug passes will gradually decrease as the slug moves around the line. The authors are presently working to develop a method of performing and interpreting these measurements.

References

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2 Grasshoff, A., 1983. Local flow of fluid and its influence on the cleaning process in cylindrical dead spaces. Kieler Milchwirtschaftlich Forschungberichte 35 (4) 471-492 (1983).